Reactive CO_2 Capture | DAC-DFM

ARPA-E Workshop

Creating solutions for a NET ZERO world

February 2-3, 2022

Raghubir Gupta, Co-Founder of Susteon and Sustaera

Susteon

Susteon Business Model and Team

Susteon

MISSION

To develop and deploy decarbonization technologies by enabling disruptive innovations in **CO_2 capture and utilization** and **carbon-free H_2 production**

APPROACH

De-risk technologies through extensive prototype development and testing while securing a strong IP position

PROCESS

Connect
- Academic / National Labs
- Dept of Energy (+ other Govt. agencies)
- Industry
- Private Sector / VC

Create

Carbon Dioxide
- CO_2 Capture
- CO_2 Utilization

Hydrogen
- Blue/Green Production
- Methane Pyrolysis

Commercialize
- Discovery & Commercial Value Decision
- Leverage Industry and Labs to Fail Fast
- Understand and Develop Go-To-Market Plan

RESEARCH & DEVELOPMENT TEAM


Raghubir Gupta
President & Co-Founder


S. James Zhou
Senior Director


Cory Sanderson
Process Technologist


Vasudev Haribal
Research Engineer


Aravind Rayer
Research Engineer


Jonathan Peters
Sr. Process Engineer


Arnold Toppo
Research Engineer


Tyson Lanigan-Atkins
Materials Scientist


Jian Zheng
Sr. Research Engineer


Andrew Tong
Sr. Research Engineer


J.P. Shen
Sr. Chemist


Gary Howe
Lab Director

BUSINESS & OPERATIONS TEAM


Shantanu Agarwal
President / Co-Founder


Rich McGivney
Chief Financial Officer


Sudarshan Gupta
Commercial Lead


Brian Alexander
Director, Contracts & Legal Affairs


Arleane McKiver
Executive Assistant

Current Technology Portfolio

Susteon

More than $50M has been invested in the R&D for the development of technologies

Green / Blue Hydrogen Production

Natural Gas to H_2

Hydrogen production from natural gas with <3 kg CO_2 / kg H_2

- **Methane Pyrolysis**
- Low Temperature **Plasma Reforming** with pure CO_2 production

CO_2 Capture

CO_2 Capture Technology

Novel CO_2 capture agents that allow significant reduction in separation energy

- **Point Source Capture**
- **Direct Air Capture**

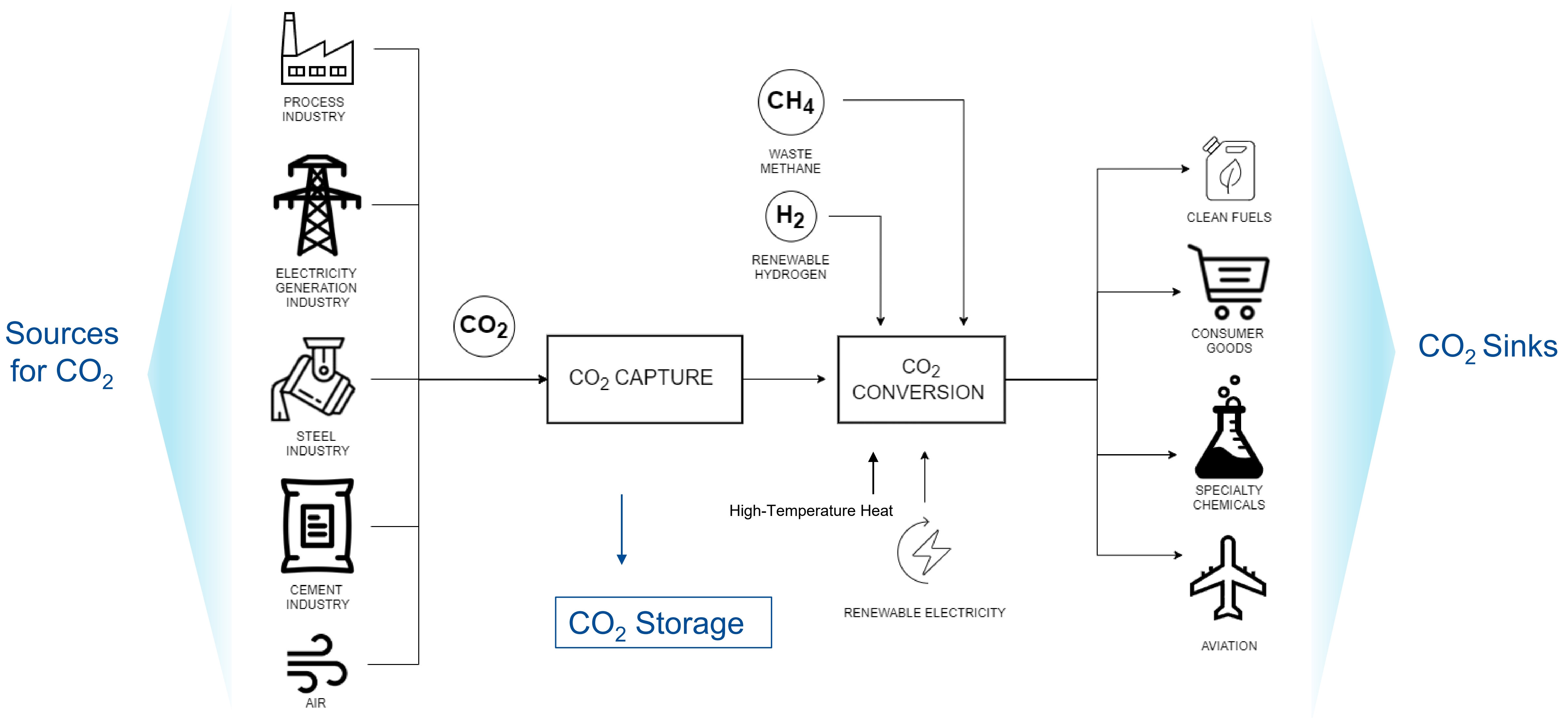
CO_2 Utilization

CO_2 to Chemicals

Conversion of CO_2 into chemicals, fuels and construction materials

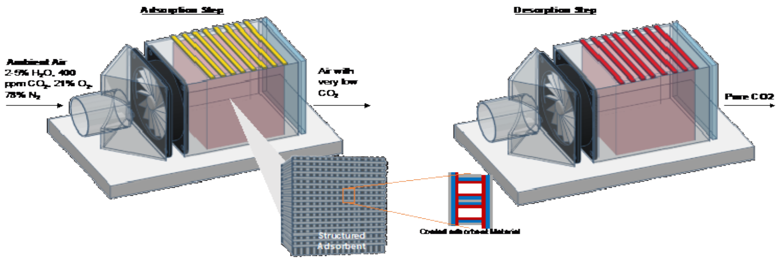
- **Sustainable Aviation Fuel**
- **Ethylene / Propylene**
- **Concrete Masonry Units**
- **Methanol / Dimethyl Ether**

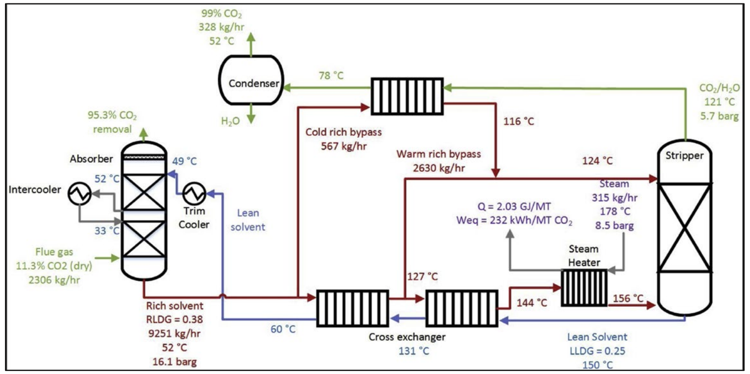
Our Vision on CO_2 Capture and Utilization

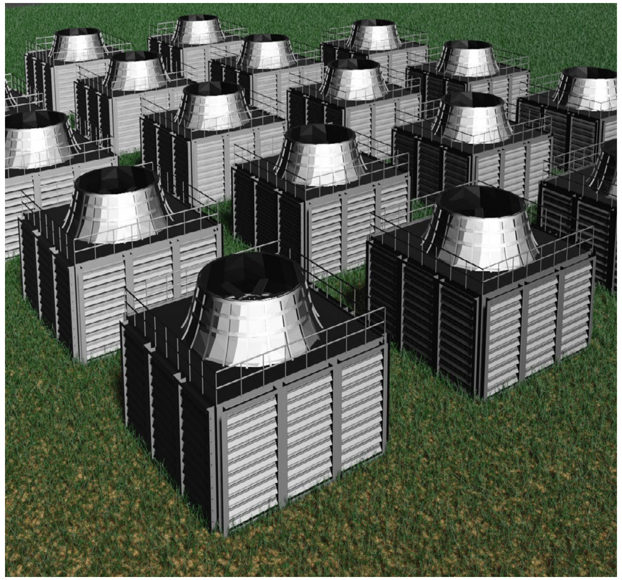


Extensive Experience in CCUS

- Susteon team has more than 100 man-years of experience in CO_2 capture technologies
- Developed technologies using
    - Solvents
    - Sorbents
    - Membranes
    - Hybrid systems
- Removal of CO_2 from point sources and process streams
    - CO_2 removal from syngas (H_2/NH_3 production)
    - Flue gas from coal combustion
    - Flue gas from NGCC
    - Flue gas from Cement plant
- CO_2 removal from air (DAC)
- Designed, built, and operated a 1,000 ton/day CO_2 capture plant at Polk Power site in FL.
- CO_2 utilization to produce value-added products







Current DAC Technologies

Susteon

Direct Air Capture (DAC) Technologies

1. Membranes

2. Solid Sorbents

- Alkali metals (Sustaera) (chemisorption)
- Amines (chemisorption)
- Activated carbons (physisorption)
- Zeolites (physisorption)
- MOFs (physisorption)
- Resins (humidity swing)

3. Electrochemical

4. Cryogenic

- Arctic/Antarctica
- Tropopause

5. Kelp/Seaweed-Based Capture

6. Liquid Solvents

- KOH
- Retrofitting cooling towers
- Amines

7. Ocean Capture

- Electrodialysis
- Electrolysis

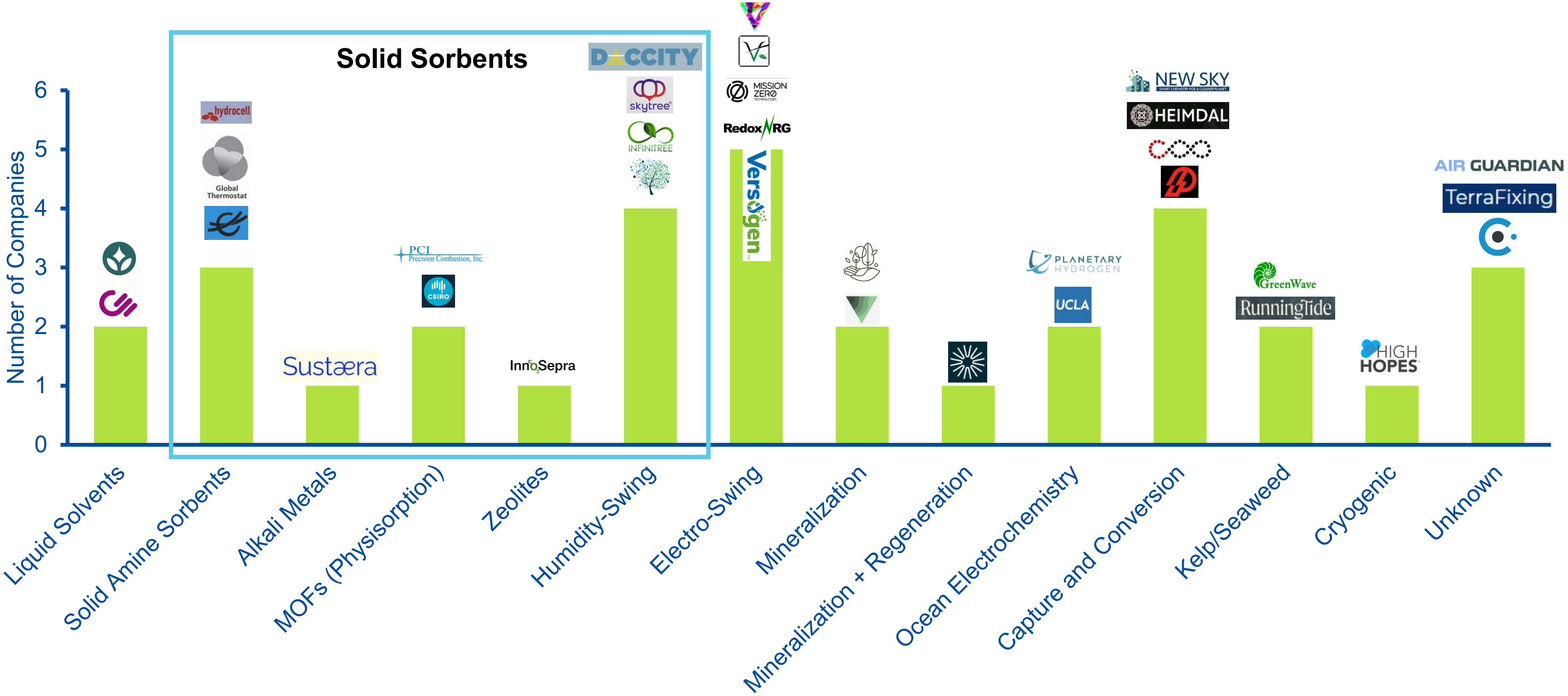
8. Carbon Mineralization (+ Regeneration)

- Coastal
- Forests
- Land

Established and Emerging DAC Technology Players

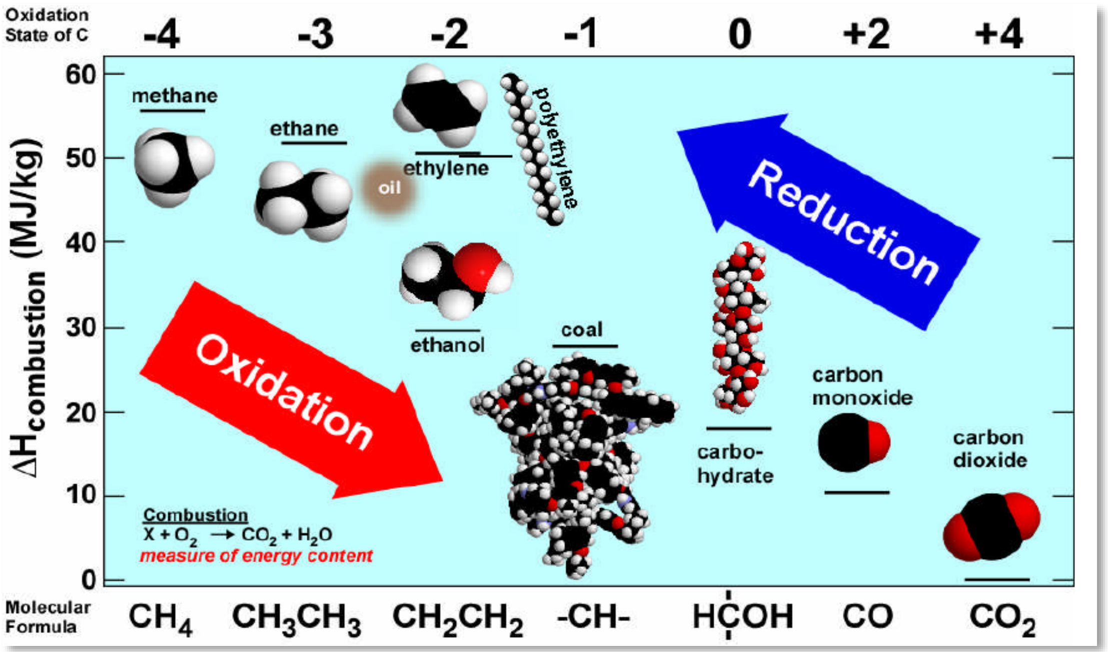
Susteon

- Big 3 (Carbon Engineering, Global Thermostat, Climeworks)
- 29 smaller companies, many of which have emerged in the last couple of years



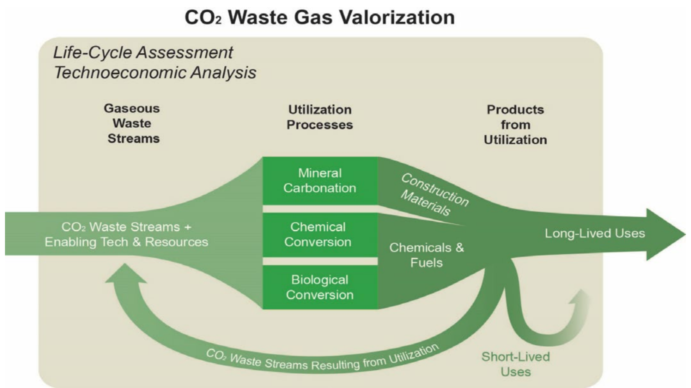
CO_2 Utilization Challenge

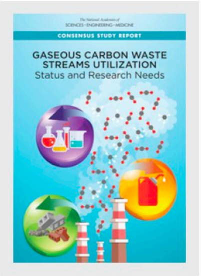
Susteon



Thermochemical Challenges

Reliable, inexpensive carbon-lean energy



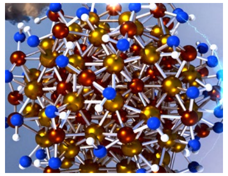


Gaseous Carbon Waste Streams Utilization: Status and Research Needs (2019)

DETAILS

256 pages | 7 x 10 | PAPERBACK

ISBN 978-0-309-48336-0 | DOI 10.17226/25232



Catalysts

$CO_{2(g)}$
(-394 kJ/mole)

Thermodynamic Stability of CO_2

Partnership with DOE and Columbia University

Susteon

NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

U.S. DEPARTMENT OF ENERGY | Fossil Energy and Carbon Management

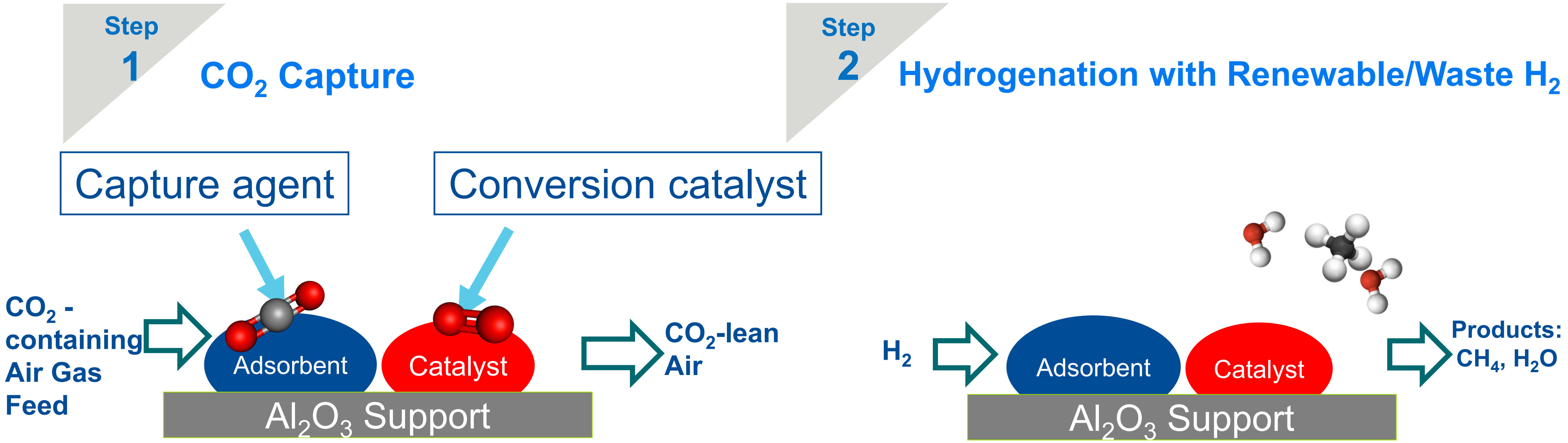
SBIR Grant: DE-SC0020795

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Robert Farrauto **Chae Jeong-Potter** **Monica Abdallah**

Reactive Direct Air Capture (DAC) of CO_2

Dual Functional Material (DFM) captures CO_2 and releases into CH_4 upon conversion



Overall reaction:

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ $\Delta H = -165$ kJ/mol of CO_2

Reactive Capture Technology Development Pathway

Susteon

Key Design Elements

1. CO_2 Adsorbent
2. Methanation Catalyst
3. Hydrogen
4. Low Pressure
5. Low ΔP
6. Simple Design

Process Design Requirements

- Low cost, widely available
- Relatively high capacity (~ 4 wt%)
- Ambient temperature/humidity CO_2 adsorption
- Low regeneration energy
- Long-term, multi-cycle stability
- Alkali metal-oxides

11 Na Sodium 22.990

19 K Potassium 39.098

- Alkaline earth metal-oxides

12 Mg Magnesium 24.305

20 Ca Calcium 40.078

56 Ba Barium 137.327

Reactive Capture Technology Development Pathway

Susteon

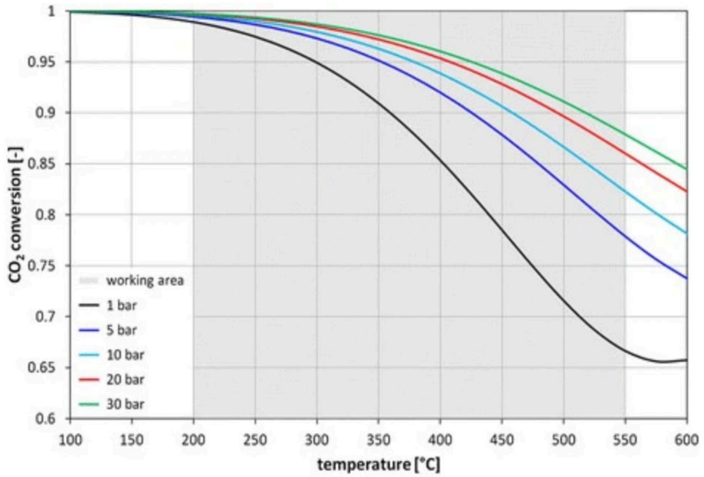
Key Design Elements

1. Adsorbent
2. **Catalyst**
3. Hydrogen
4. Low Pressure
5. Low ΔP
6. Simple Design

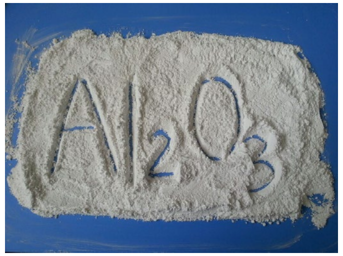
Process Design Requirements

- Overall reaction:
  $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
- Catalyze the Sabatier reaction

28 Ni Nickel 58.693	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906



- High surface area support



Carbon
6
C
12.011

- Long-term, multi-cycle stability in between oxidative and reducing environments
- Low temperature methanation 180 – 300 °C

Reactive Capture Technology Development Pathway

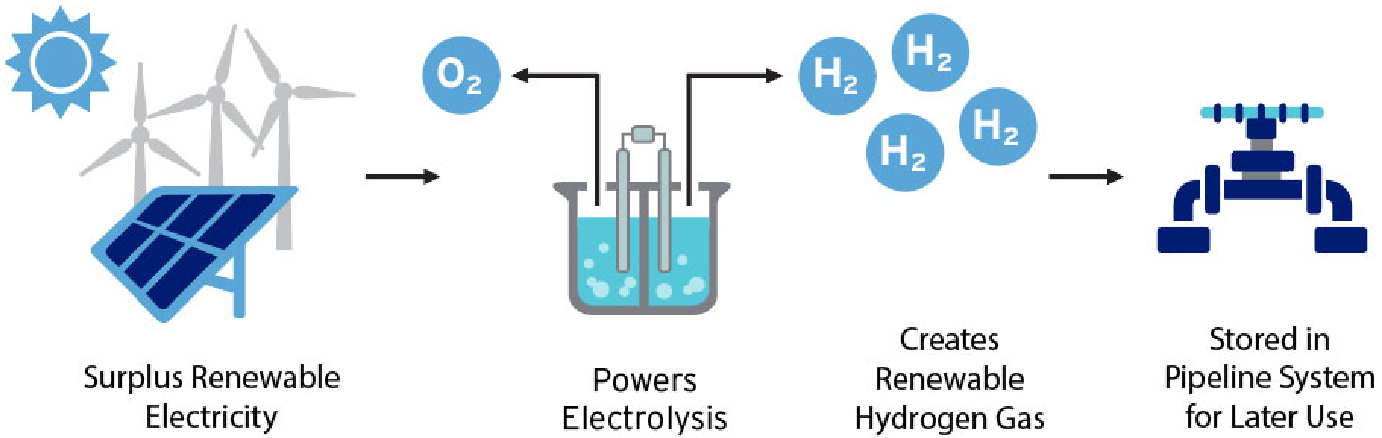
Susteon

Key Design Elements

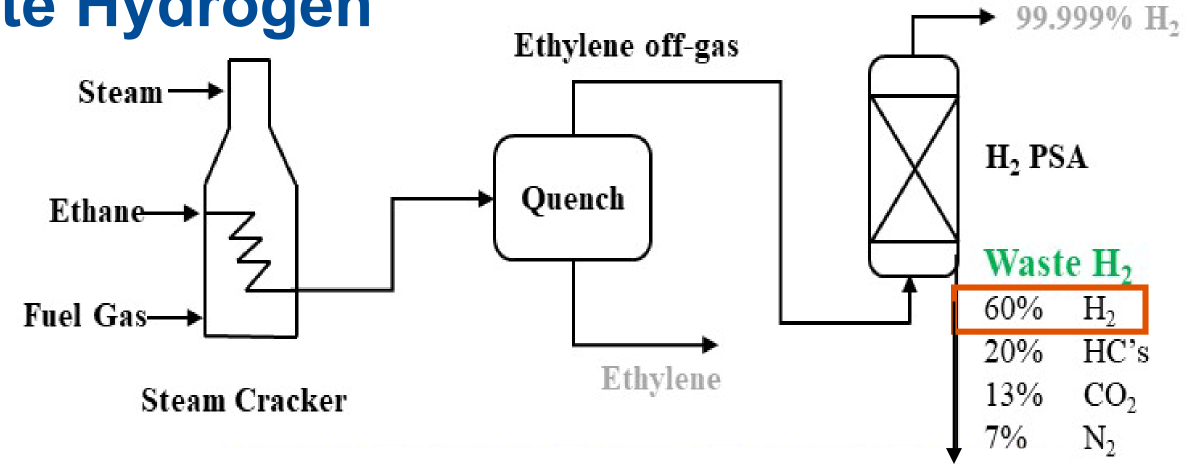
1. Adsorbent
2. Catalyst
3. **Hydrogen**
4. Low Pressure
5. Low ΔP
6. Simple Design

Process Design Requirements

Electrolysis



Waste Hydrogen



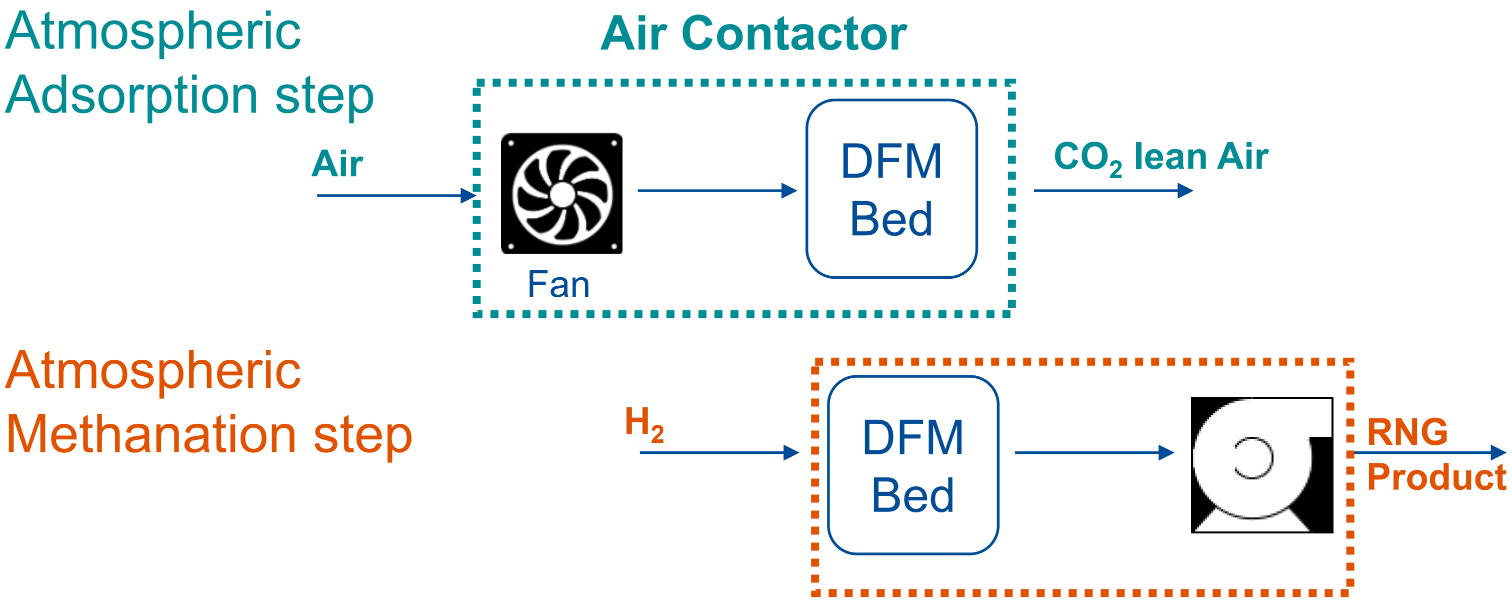
Reactive Capture Technology Development Pathway

Susteon

Key Design Elements

1. Adsorbent
2. Catalyst
3. Hydrogen
4. **Low Pressure**
5. Low ΔP
6. Simple Design

Process Design Requirements



- Avoid need for upstream compressors
  - Air compression not needed for adsorption
  - H_2 compression not needed for regeneration
    - Low pressure electrolysis
    - Low pressure waste hydrogen
- Reduce CAPEX and OPEX

Reactive Capture Technology Development Pathway

Susteon

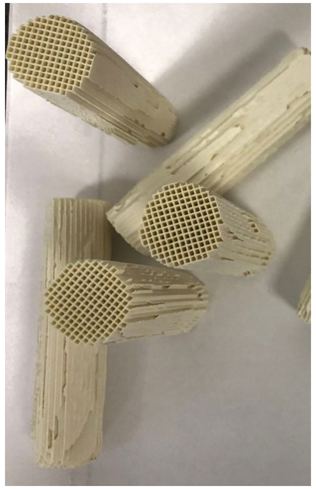
Key Design Elements

1. Adsorbent
2. Catalyst
3. Hydrogen
4. Low Pressure
5. **Low ΔP**
6. Simple Design

Process Design Requirements

- Maximize energy efficiency
- Reduce fan power demand
- Use scalable monolith supports for high surface area, low pressure drop
- Goal: 250 kWh/ton of CO_2

3/4-inch OD



Scaleup

6-inch OD

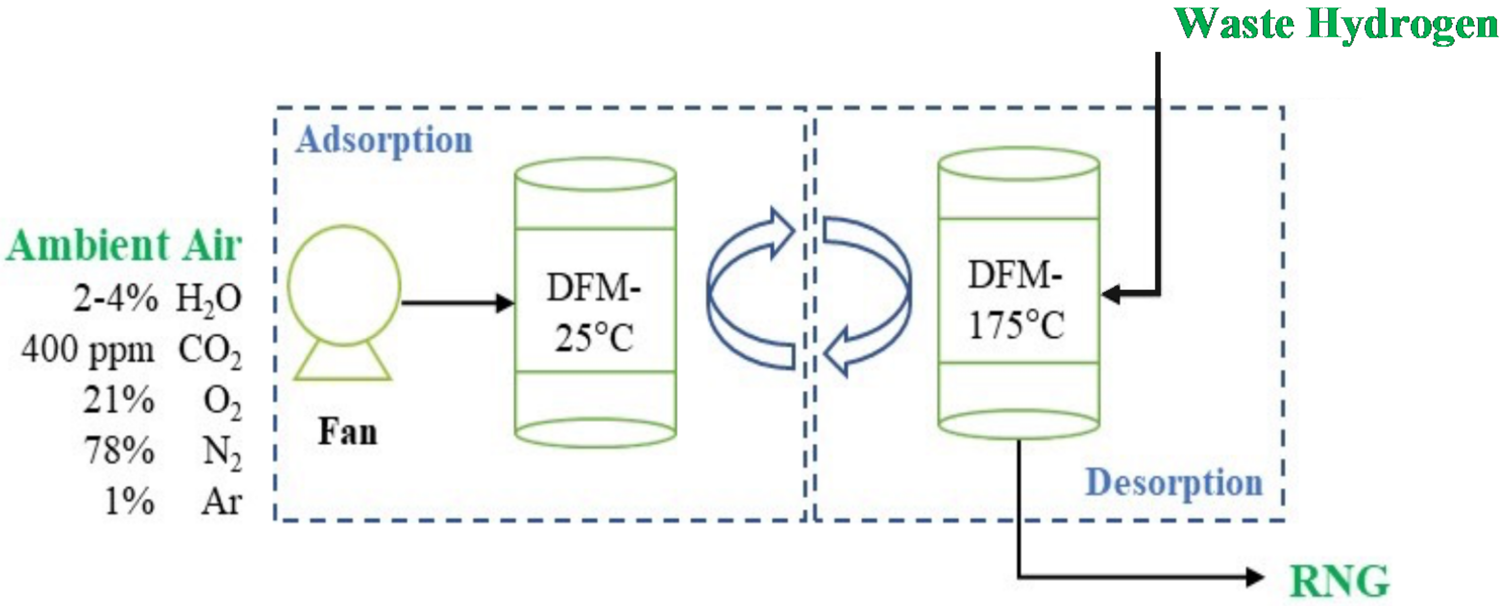
Reactive Capture Technology Development Pathway

Susteon

Key Design Elements

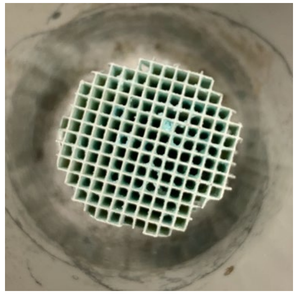
1. Adsorbent
2. Catalyst
3. Hydrogen
4. Low Pressure
5. Low ΔP
6. **Simple Design**

Process Design Requirements



Utilizing Dual Functional Materials (DFM) for reactive Direct Air Capture (DAC) of CO_2 into Renewable Natural Gas (RNG) from Waste Hydrogen

DAC-DFM Technology Development Pathway



We are here

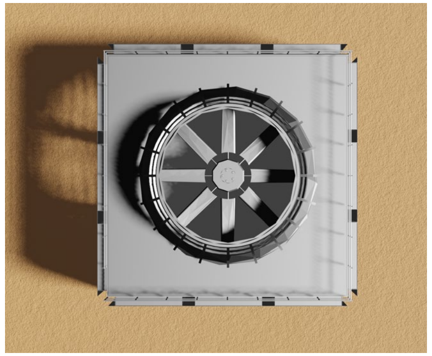
Proof of concept

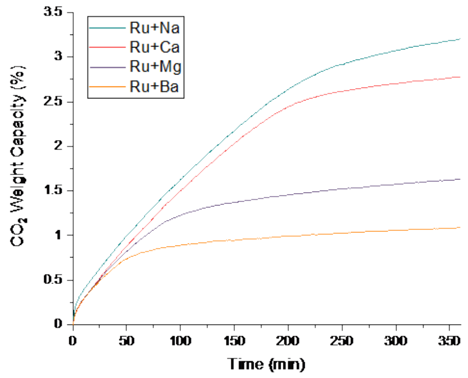
DAC-DFM granules testing

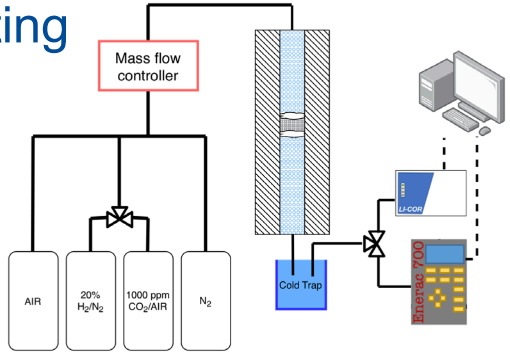
DAC-DFM washcoated monolith testing

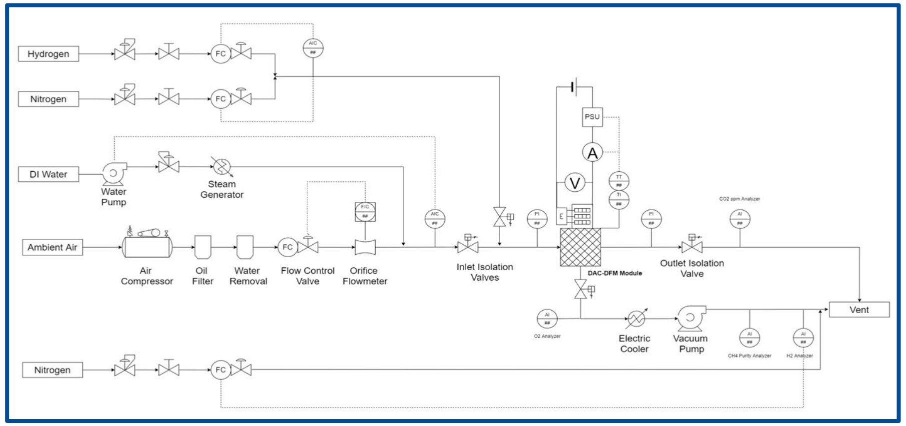
Bench-scale unit testing

Pilot-scale demo unit





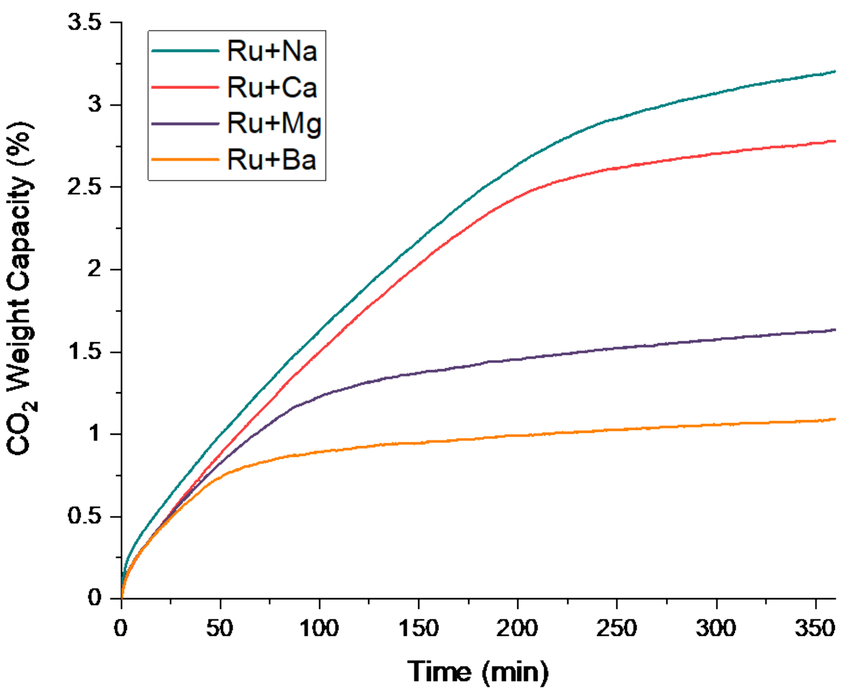




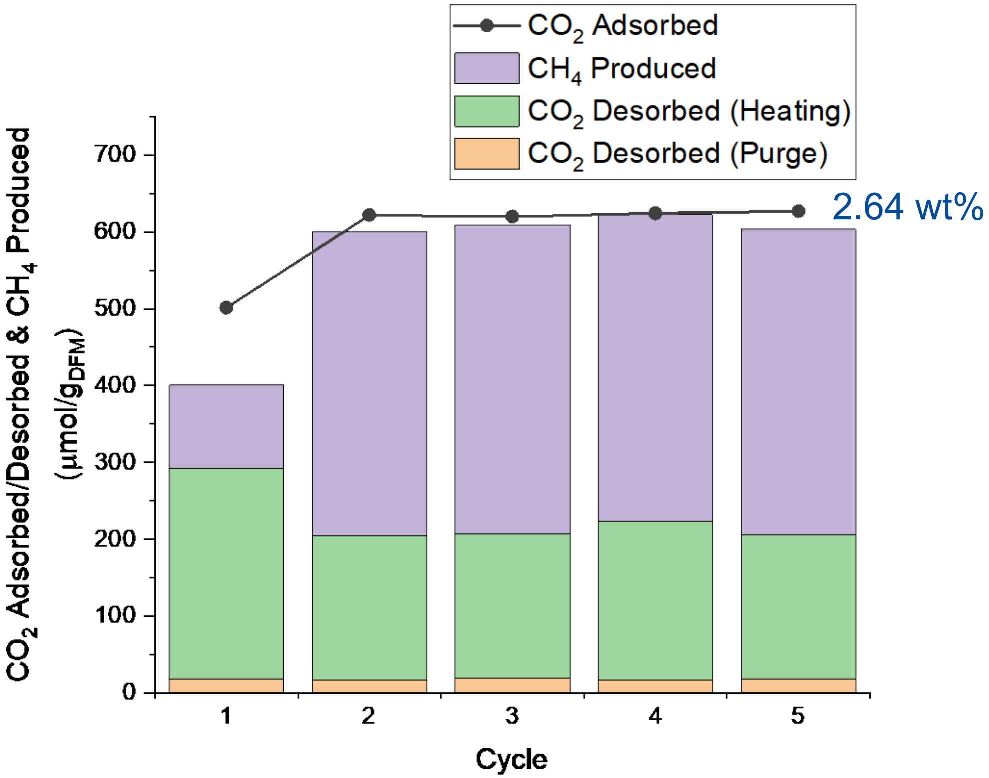
Proof of Concept: Adsorbent + Catalyst System

Susteon

Thermal gravimetric analysis: Adsorption @ 25°C on 1% Ru, 10% sorbent/Al_2O_3 granules with 375 ppm CO_2/air



Cyclic packed bed: Adsorption @ 25°C and methanation at 300°C on 1% Ru, 10% Na_2O/Al_2O_3 granules



1% Ru, 10% Na_2O/Al_2O_3 (Ru + Na, green) shows the **highest** CO_2 capture capacity (~3% weight capacity).

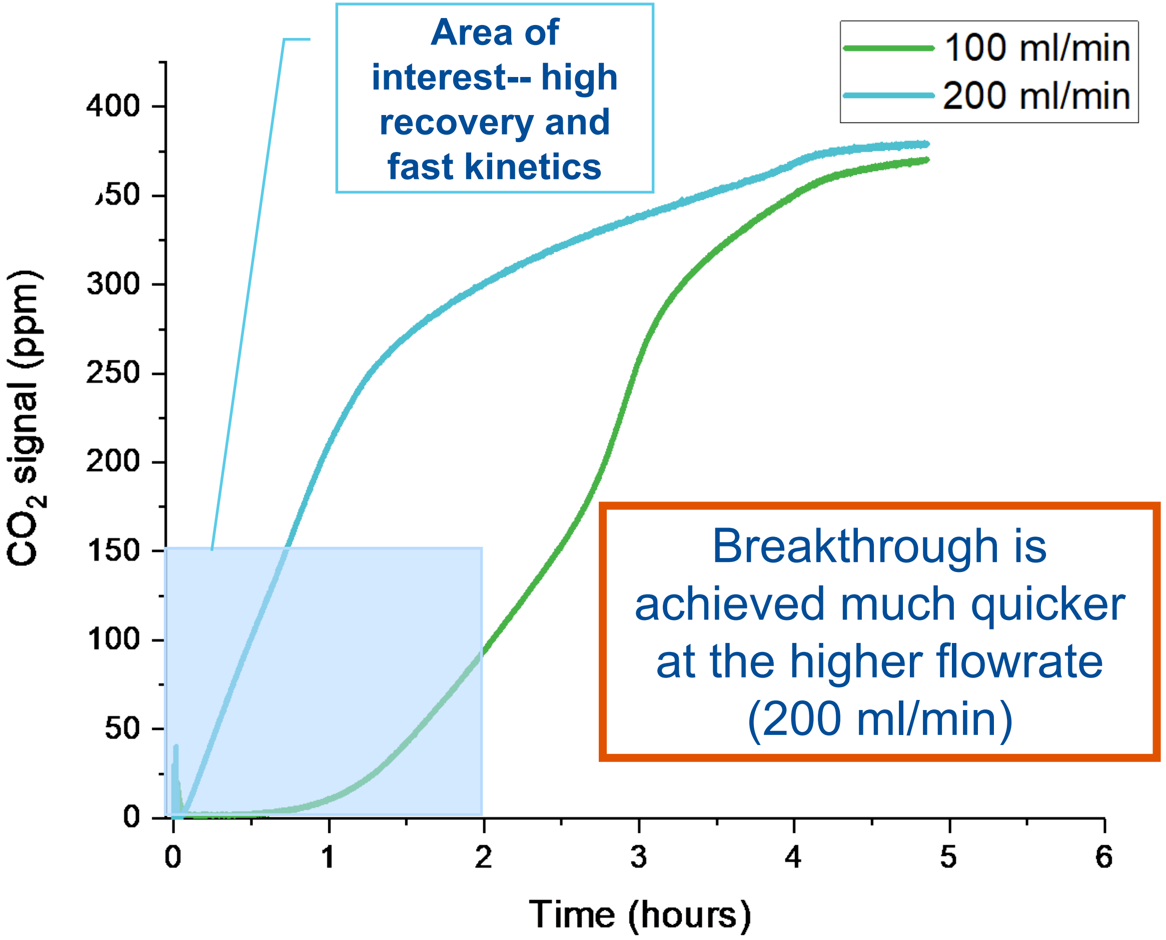
Multiple cycles in a TGA and packed bed clearly show consistent DFM regenerability with H_2 at suitable temperatures.

COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science

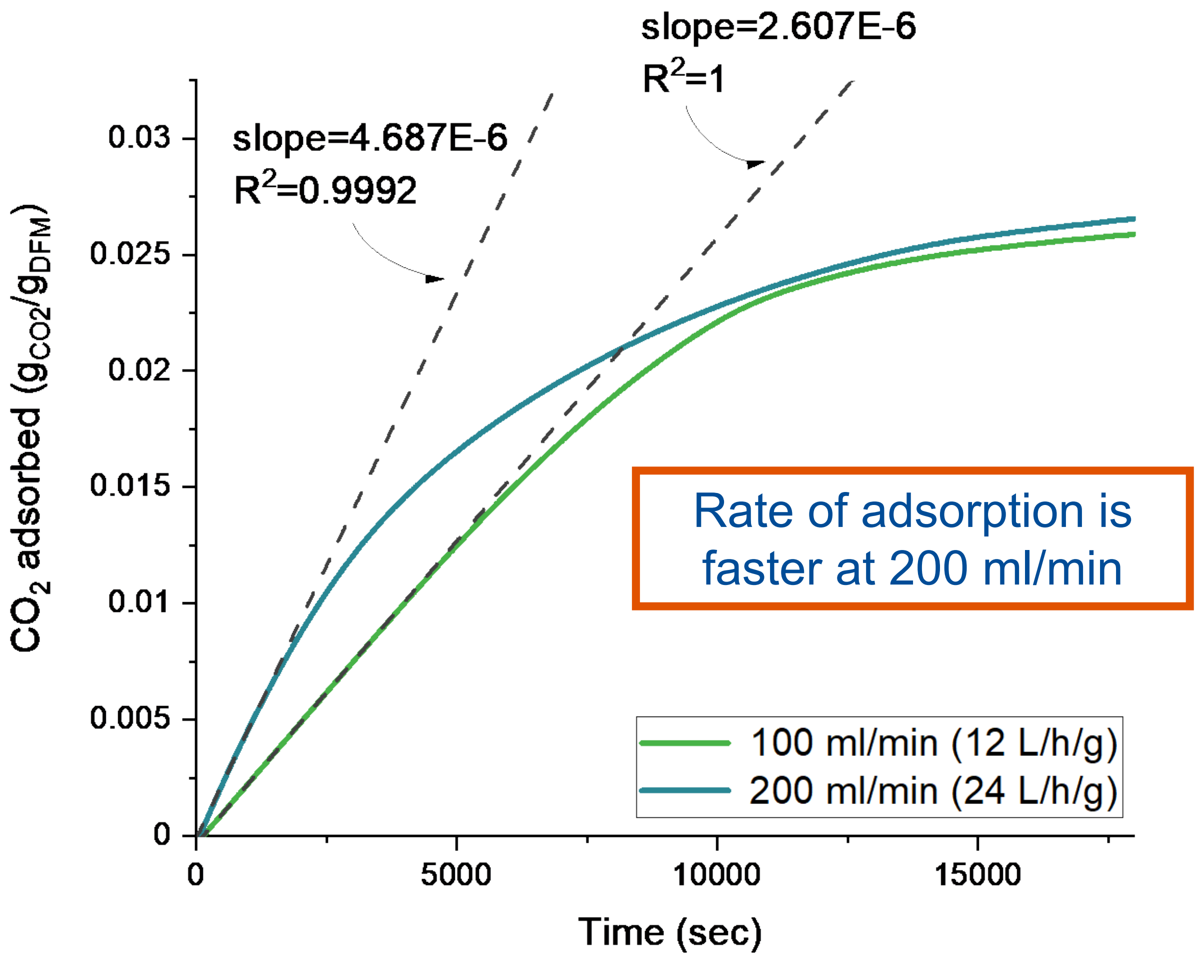
Adsorption Rate: 1% Ru, 10% Na_2O on Alumina DFM

Sample: 1% Ru, 10% Na_2O/Al_2O_3 granules

CO_2 signal during adsorption

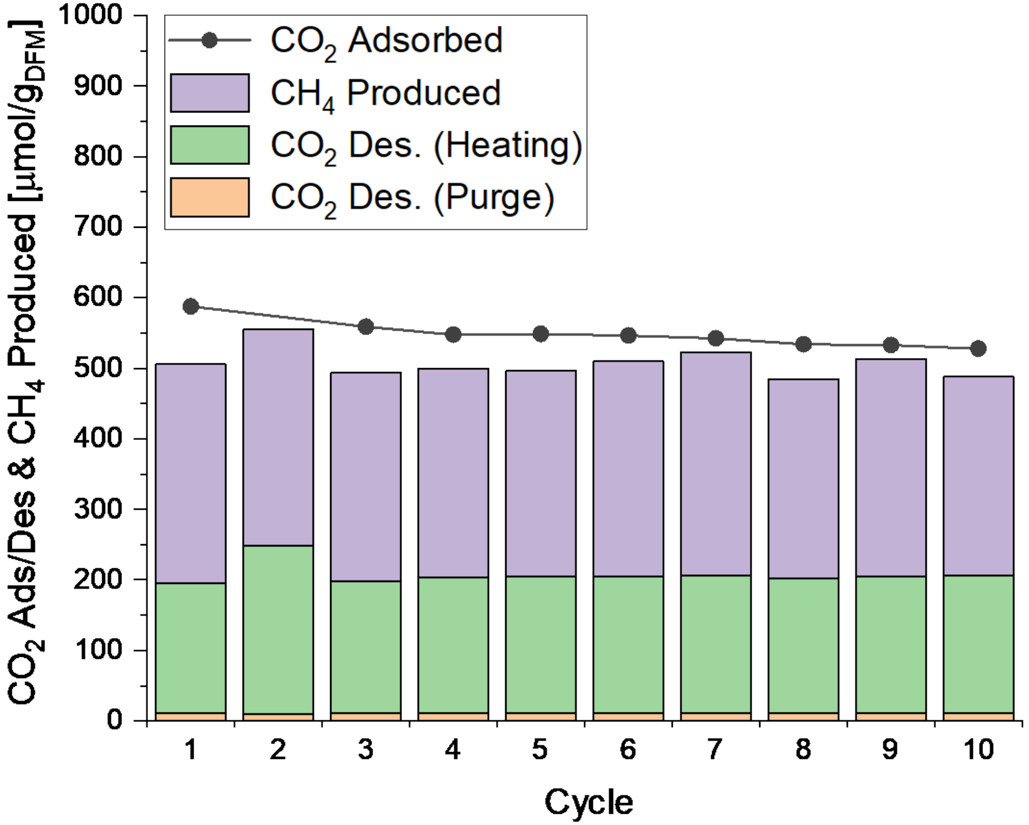


Linear fit on cumulative CO_2 adsorption curves



DFM granules development and testing

Susteon



Cyclic operation

- 0.5g of 1% Ru, 10% Na_2O/Al_2O_3 granules
- Pre-reduction: 3 hours at 300°C in 20% H_2/N_2

Cycle Step	Duration	Gas
Adsorption @ 25°C	2 hours	400 ppm CO_2/air @ 400 ml/min
Heating to 300°C	30 min	15% H_2/N_2 @ 100 ml/min
Methanation @ 300°C	2 hours	

Average CO_2 Ads.	Average CH_4 Prod.
547 µmol/g_{DFM}	300 µmol/g_{DFM}

1% Ru, 10% Na_2O DFM shows stable performance for 10 cycles of capture/methanation.

Jeong-Potter et al Applied Catalysis B: Environmental, doi:https://doi.org/10.1016/j.apcatb.2021.120990

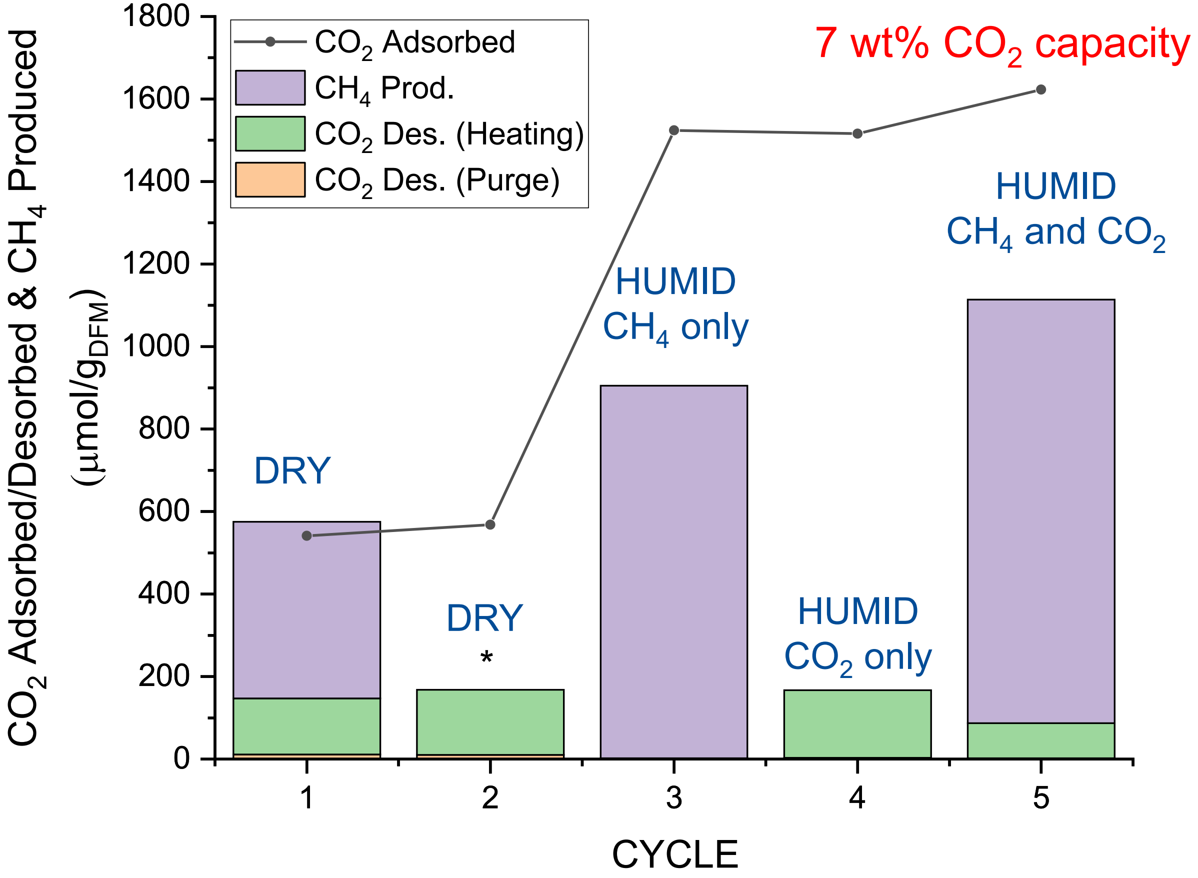
Humid Air - Experimental Results

Susteon

Ads. Condition	Avg. CO_2 Capacity	Avg. CH_4 Prod.
Dry	626 $\mu mol/g_{DFM}$	395 $\mu mol/g_{DFM}$
Humid	1521 $\mu mol/g_{DFM}$	965 $\mu mol/g_{DFM}$

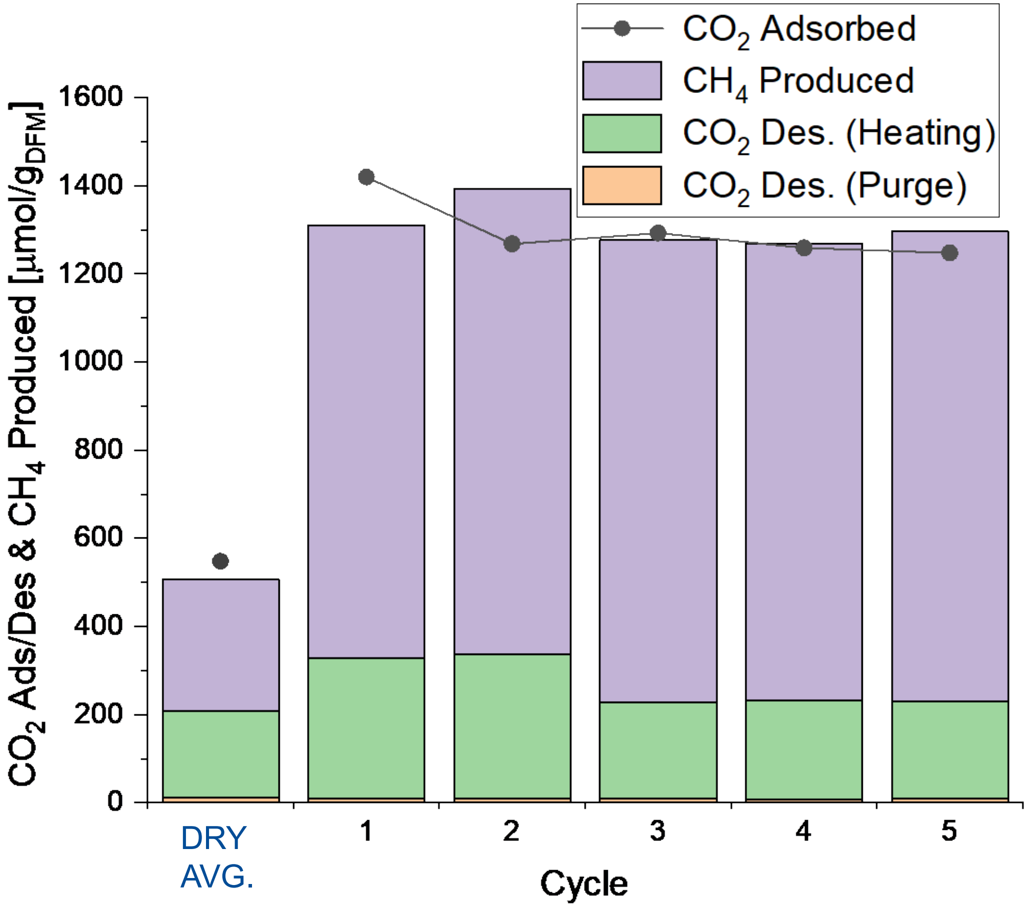
- CO_2 capture capacity increases significantly, by 2.4 times, in humid conditions.
- Methanation light off occurs around 140°C, about 40°C lower than our previous studies on Ru-Na_2O.
- We observed an approximate 45% decrease in CO_2 desorption during heating and methanation.

1% Ru, 10% Na_2O/Al_2O_3



** Note: Methane production not measured for Cycle 2.*

Improved adsorption and methanation in humid adsorption conditions



Cyclic operation

- 0.5g of 1% Ru, 10% Na_2O/Al_2O_3 granules
- Pre-reduction: 3 hours at 300°C in 20% H_2/N_2
- Adsorption in humid conditions: ~2% H_2O

Cycle Step	Duration	Gas
Adsorption @ 25°C	4 hours	400 ppm CO_2/humid air @ 400 ml/min
Heating to 300°C	30 min	15% H_2/N_2 @ 100 ml/min
Methanation @ 300°C	2 hours	

Average CO_2 Ads.	Average CH_4 Prod.
1300 μmol/g_{DFM}	1040 μmol/g_{DFM}

1% Ru, 10% Na_2O DFM improved performance in humid adsorption conditions; stable performance for 5 cycles of humid ads/methanation

Jeong-Potter et al Applied Catalysis B: Environmental, doi:https://doi.org/10.1016/j.apcatb.2021.120990

Transition to monolithic supports

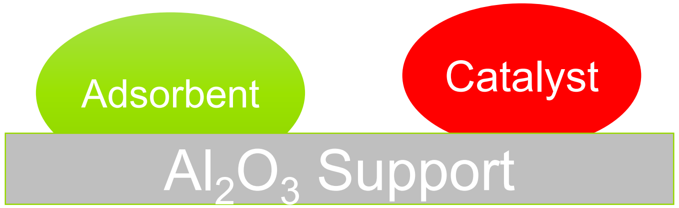
Susteon

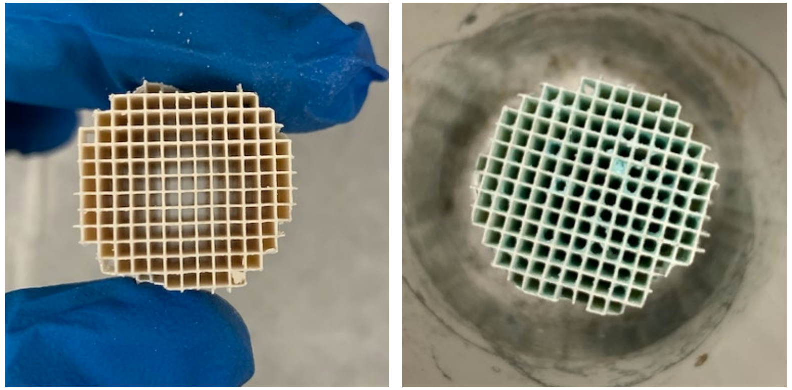
Advantages to using monoliths:

- Resistance to cracking when operating across broad temperature range
- Cost effective due to mass production
- Clear flow path results in low pressure drop relative to packed bed
- Design a process for heating only the washcoat for methanation

- Preliminary studies of CO_2 adsorption/desorption in DAC conditions using monolithic substrates are underway.
- Initial coating of TiO_2 monolith with Na_2O-impregnated alumina was very successful.

The DFM is composed of an **alkaline sorbent (Na_2O)** and **metal catalyst (Ru)** dispersed on **γ-Al_2O_3 powder.**





Monolith before (left) and after (right) washcoating

Cyclic performance of Ru, Na_2O/Al_2O_3 //monolith: Short term stability demonstrated

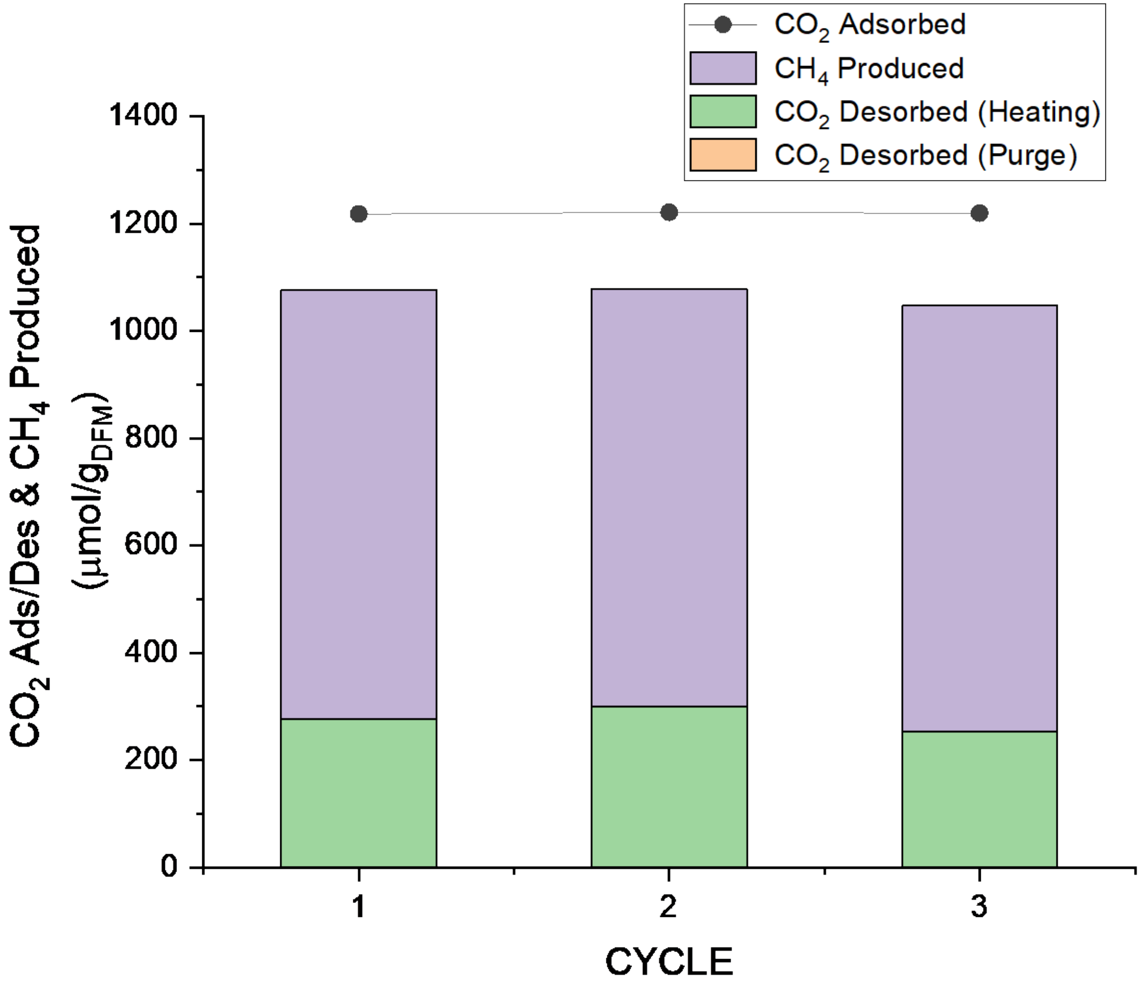
Susteon

Sample: Ru, Na_2O/Al_2O_3//monolith

- 2 g/in^3 washcoat loading
- <0.2% Ru, 40% Na_2O

- Pre-reduction: 5 hours at 300°C in 20% H_2/N_2
- All cycles in humid condition ~2% H_2O

Step	Time	Gas	Flowrate
Adsorption (25°C)	3 hr	400 ppm CO_2/ humid air	24 L/h/g (353 ml/min)
Purge (25°C)	15 min	Pure N_2	6.8 L g^{-1}h^{-1} (100 ml/min)
Heating (10°C/min)	30 min	15% H_2/N_2	9 L/h/g (133.3 ml/min)
Methanation	1.5 hr	15% H_2/N_2	9 L/h/g (133.3 ml/min)



Process Cycle Design - Air Contactor & Regenerator

Susteon

Cycle Steps & Time (Example Case)

Adsorb ~ 30-60 mins

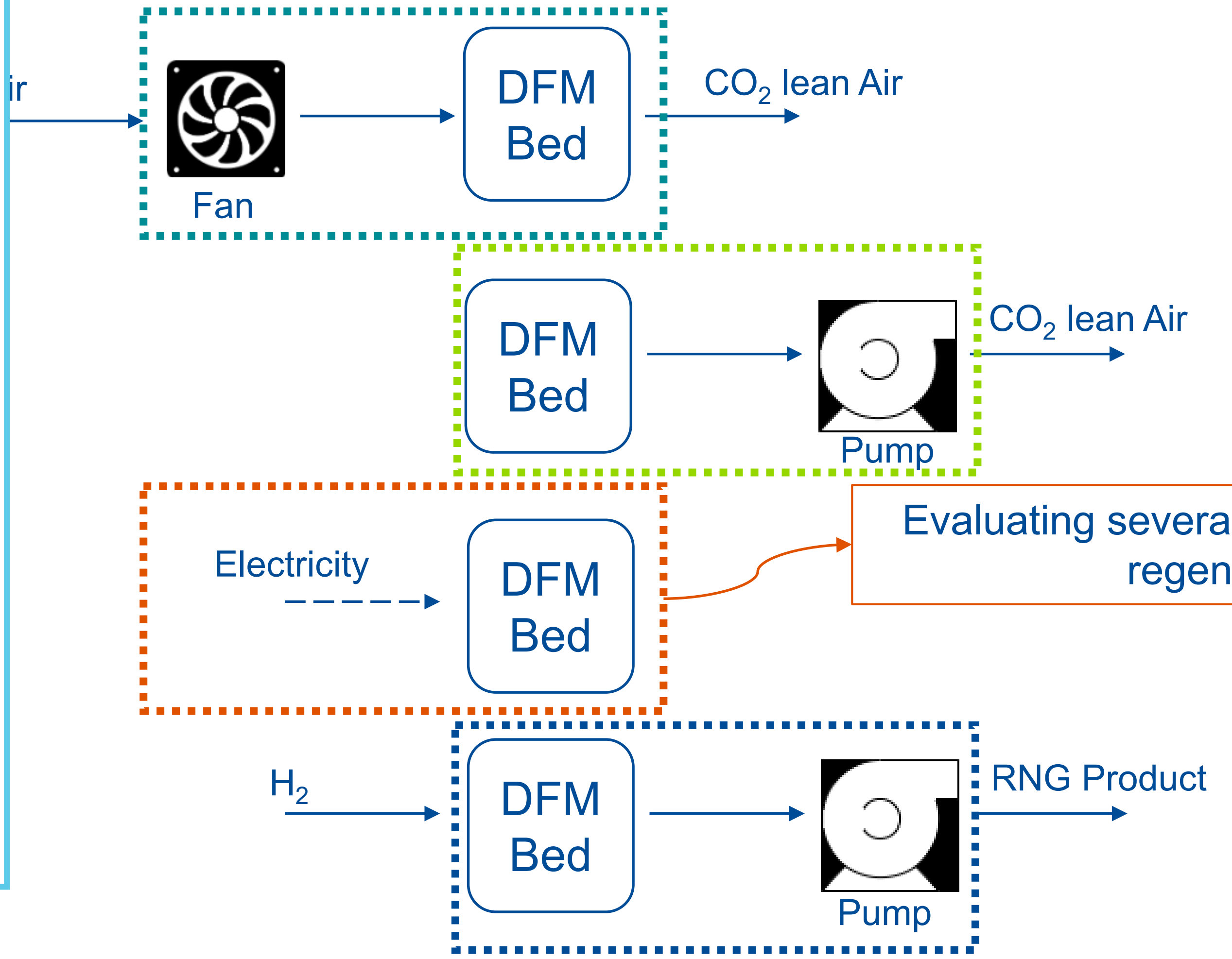
Purge ~ 1-2 mins

Heat ~1-2 mins

RNG Production ~5 mins

Air Contactor

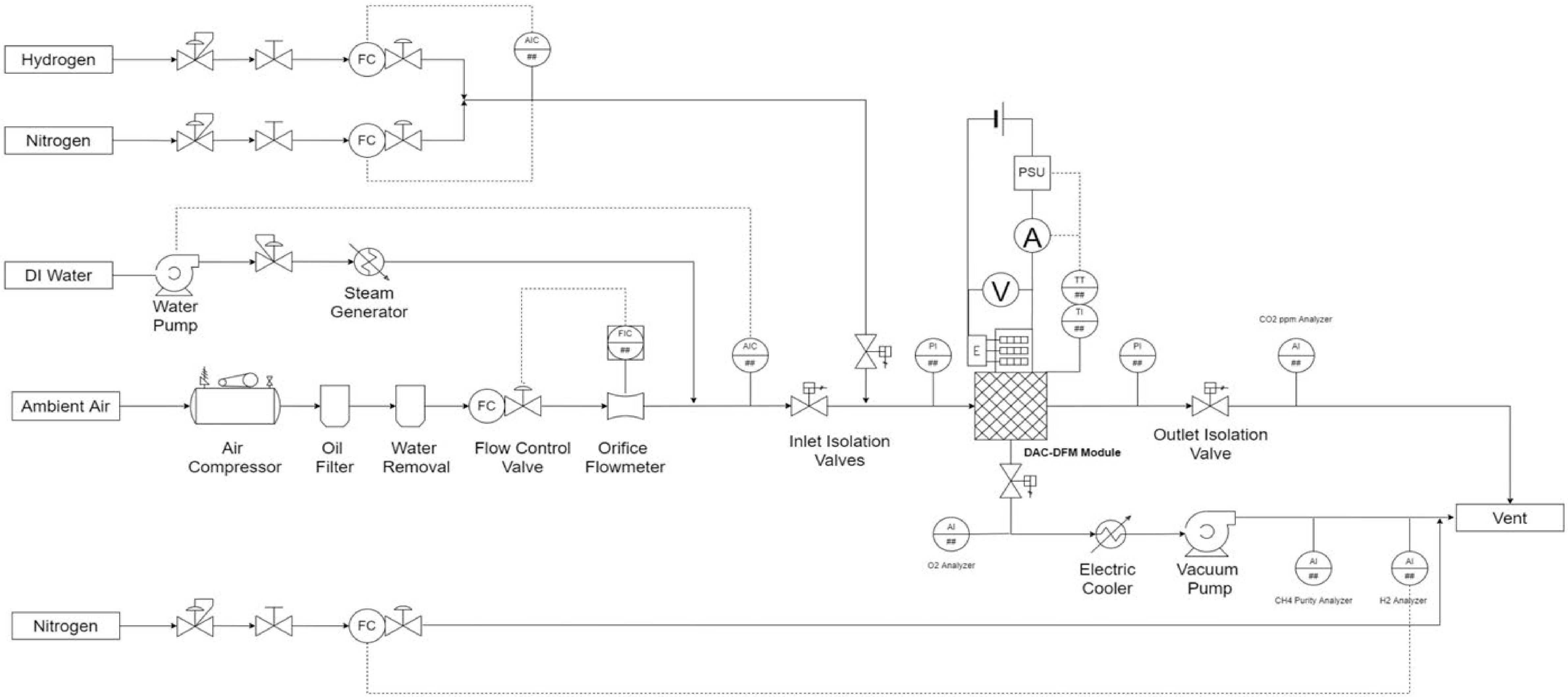
Evaluating multiple options for air contactor design, regeneration method and cycle design to reach the capture cost target.



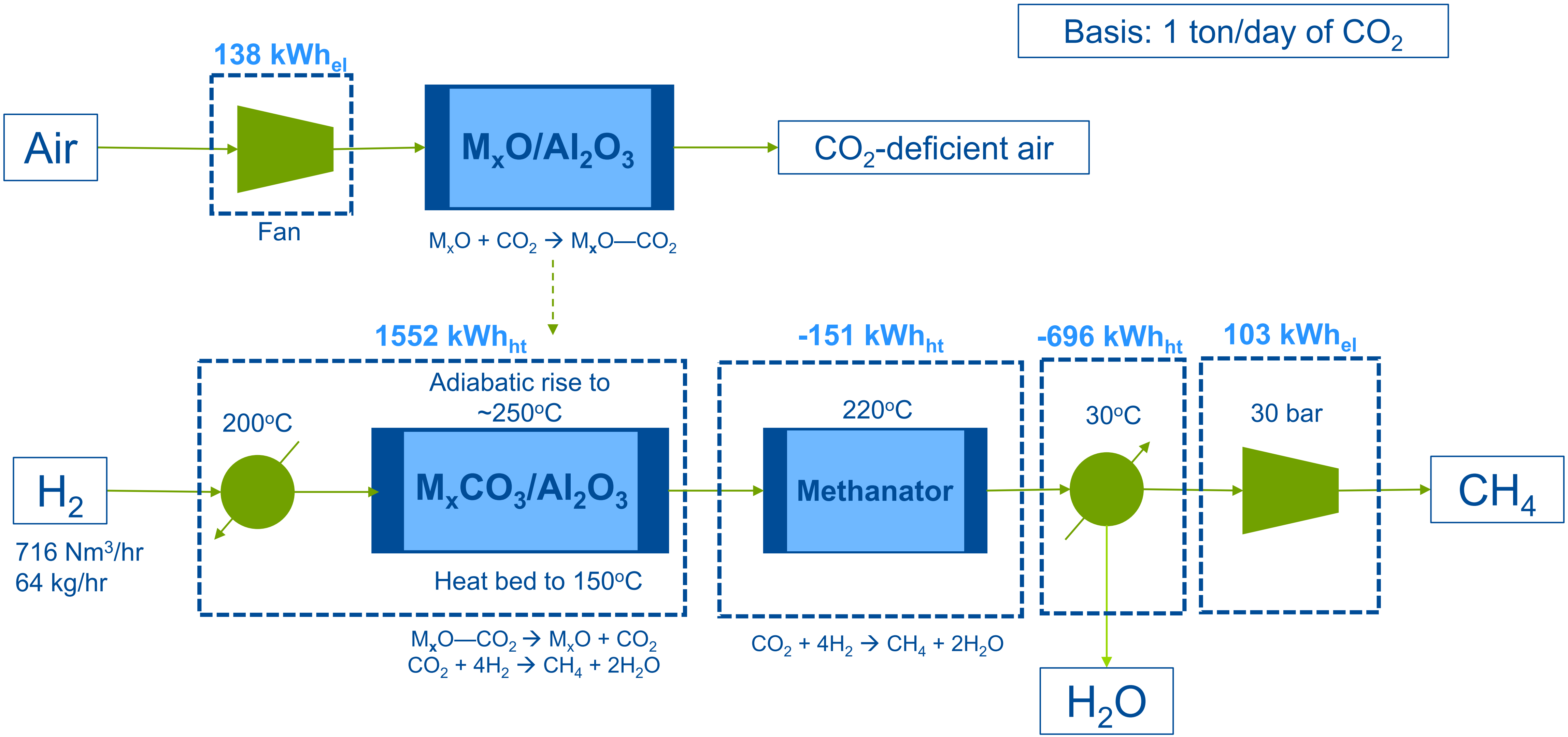
Evaluating several options for sorbent regeneration

DAC-DFM Bench Scale Test Unit PFD

Susteon



Preliminary Process Design- PFD

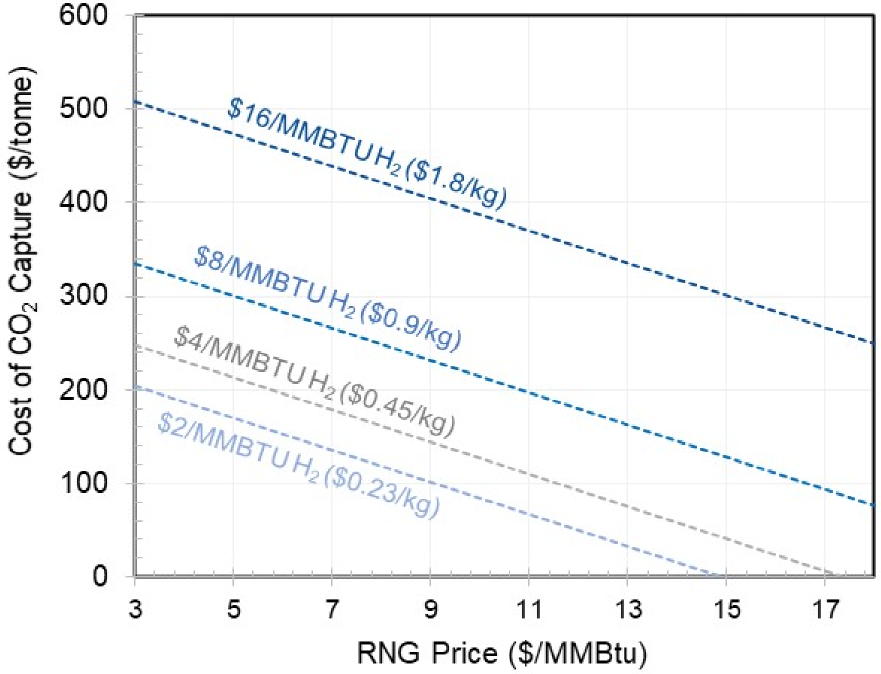


Preliminary TEA

Susteon

Parameter	Units	Value
Kinetic Rate	g CO_2/g DFM/min	2.81E-04
Direct Air Capture CO_2 Rate	tonne/day	100
Waste H_2 Flowrate	tonne/day	19
Assumptions		
Electricity to Heat Efficiency	%	75
Electricity Price	$/kWh	0.03
Waste H_2 Price	$/MMBtu	2
Capital Recovery Factor	%	12.4
Results		
TOC	$44,748	$ thousands
OPEX	56%	of total cost
CAPEX	42%	of total cost
Electricity intensity	3428	kWh/ton-CO_2
RNG Production	tonne/day	36
	MMBtu/day	560,238
RNG Selling Price	**$/MMBtu**	**15.0**
CO_2 Cost	**$/tonne**	**0**

Cost of CO_2 Capture sensitivity analysis of DAC-DFM Technology as a function of H_2 and RNG price.



The cost of CO_2 capture is below the DOE target of $100/tonne at various RNG prices from $9 to $17/MMBtu and waste H_2 between $2 and $8/MMBtu ($0.23/kg and $0.9/kg)

Susteon’s DAC Technology Spinout-- Sustaera

Sustæra

Our Solution

Direct Air Capture using:

- Non-amine sorbent for CO_2 capture
- An integrated selective heating mechanism
- A low pressure drop support

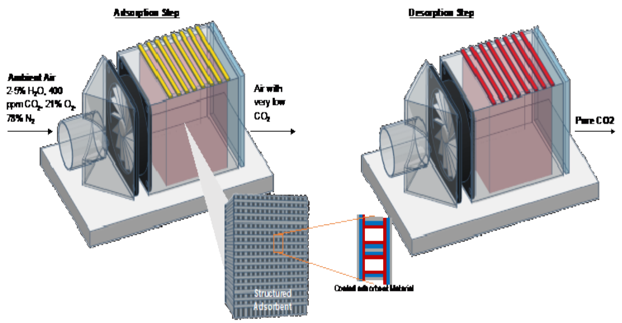
Resulting in:

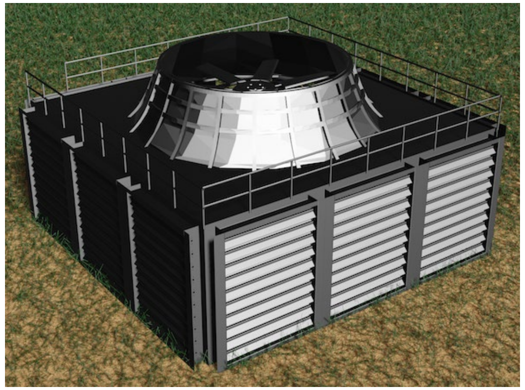
- A pathway to < 2,000 kWh/ton of CO_2
- CapEx target <~$600/ton-yr

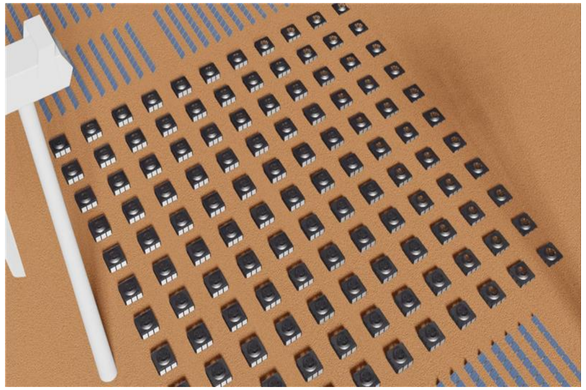
Key Differentiators

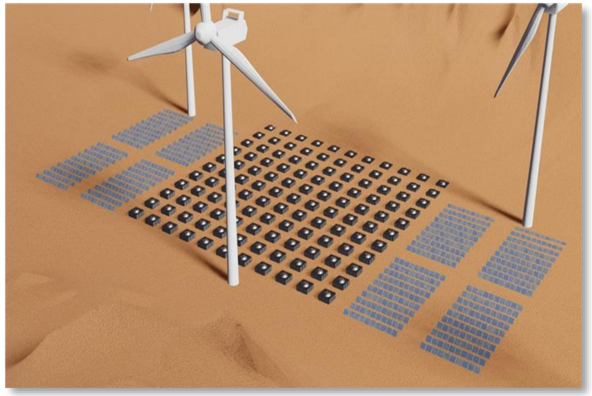
1. Energy provided exclusively by renewable sources (solar, wind)
2. Abundantly available, low-cost capture agent (alkali metal based)
3. Low energy of desorption by controlling the chemistry (~-65 kJ/mol)
4. Fast kinetics of adsorption and desorption
5. Beneficial effect of moisture in ambient air
6. Innovative, highly efficient heating to minimize heat losses
7. Scalability using existing supply chain
8. Strong IP portfolio

Conceptual Design









Funding + Customers

Sustaera

Green | Climate Adaptation

Gates-Backed Fund Invests in Carbon Capture Startup Sustaera

The company, which completed a $10 million funding round, has secured Stripe as its first customer.

- Raised **~$1.5M in Grant Funding** from:

U.S. DEPARTMENT OF ENERGY
Office of Fossil Energy

- Raised **$10M in Series A** funding from:

Breakthrough Energy

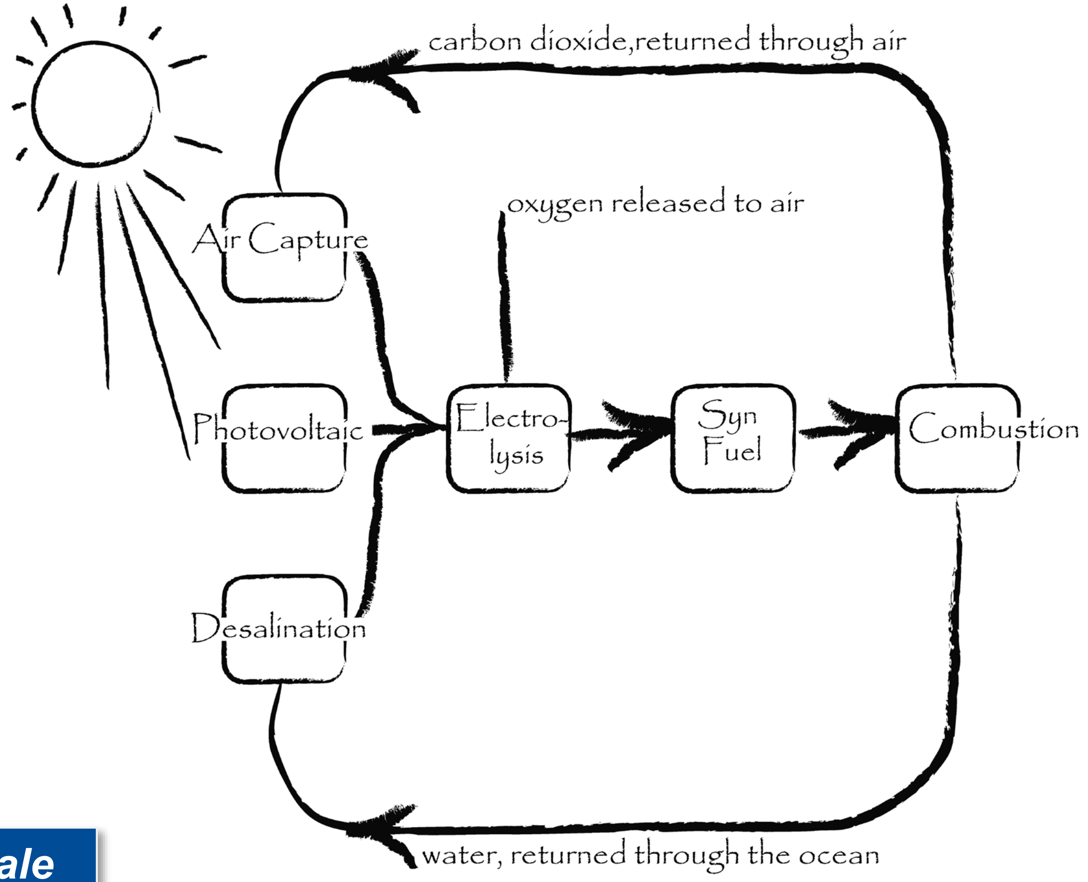
The Grantham Environmental Trust's
Neglected Climate Opportunities

- Sold **700+ tons of CO_2 Removal** to:

stripe

Circular Carbon Economy – Multi-trillion Dollar Opportunity

- Stop climate change, return from a CO_2 overshoot, and replace fossil fuels with sustainable, synthetic fuels made with renewable energy
- **Replace fossil fuels with liquid carbon-based fuels**
    - Inputs are CO_2, H_2O and intermittent renewable energy
    - Cycle 10 – 50 Gt CO_2/year worldwide through fuels
    - Cycle closes at least in part through the environment
- **Restore 100 ppm of excess CO_2 from the atmosphere**
    - Remove waste fossil carbon from the environment
    - Safe and permanent storage of 40 Gt CO_2/year for 40 years



Only direct air capture has the potential capacity and scale to close the carbon cycle and remove excess carbon

Lackner, 2019

Thank you

Raghubir Gupta

Cofounder / President, Susteon | Sustaera

rg@susteon.com

Creating solutions for a NET ZERO world

www.susteon.com